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A SIMPLE THEORY OF BIMODAL STAR FORMATION◇

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ABSTRACT. We present a model of bimodal star formation, wherein massive stars form in giant molecular clouds (GMC), at a rate regulated by supernova energy feedback through the interstellar medium, the heat input also ensuring that the initial mass function (IMF) remains skewed towards massive stars. The low mass stars form at a constant rate. The formation of the GMC is governed by the dynamics of the host galaxy through the rotation curve and potential perturbations such as a spiral density wave. The characteristic masses, relative normalisations and rates of formation of the massive and low mass modes of star formation may be tightly constrained by the requirements of the chemical evolution in the Solar Neighborhood. We obtain good fits to the age metallicity relation and the metallicity structure of thin disk and spheroid stars only for a narrow range of these parameters.

1. THE MASSIVE STAR FORMATION RATE

The effects of massive stars on the surrounding interstellar medium and subsequent star formation may be envisaged to be either to *suppress* further star formation for some time by destroying the cold (molecular) gas from which stars are presumed to form, or to *induce* further star formation through the increase in pressure compressing and destabilising clouds. These two effects in fact operate simultaneously, leading to self regulated (massive) star formation (cf. Cox 1983; Franco and Cox 1983; Dopita 1985). The lower mass stars are effective over much longer timescales and may be neglected for the regulation of the formation of short-lived stars. Assuming that the most important energy injection process is due to supernova explosions, which maintain a velocity dispersion in the system of GMC that governs the cloud-cloud collision time and hence energy dissipation and star formation time, leads to the following dependence of global massive star formation rate (SFR) per unit (molecular) gas mass on the surface densities (Σ) of total material, and gas :

$$\frac{\dot{M}_*}{M_{gas,CO}} \sim (\Sigma_{tot}\Sigma_{gas,CO})^{1/2}$$

The self regulation allows one to understand why only a small fraction of GMC cores have associated HII regions (Solomon, Sanders and Rivolo 1985; Scoville, Sanders and Clemens 1986) *ie.* why massive star formation is in this sense inefficient.

The massive SFR in external galaxies may be estimated from the UV flux, or the far IR assuming it is mainly due to dust reradiation of the UV from massive stars. Unfortunately, large discrepancies in these two estimates exist for the galaxies that have measurements of the quantities in the above equation, which may indicate either that a significant fraction of the IRAS flux is due to a cirrus component of dust heated by the general stellar radiation field, or that extinction problems remain with the quantitative interpretation of the UV, or both. Thus a direct quantitative testing of this relation is not yet possible.

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2. THE RADIAL DEPENDENCE OF GMC AND MASSIVE STARS.

The dependence of the global massive SFR on total surface density found above suggests that the rotation curve may be of importance. Many models for the formation of GMC complexes analyse the effect of a spiral density wave and postulate that the potential causes an increase in the lengthscale which is gravitationally unstable, or simply aids the coagulation of small diffuse clouds of either atomic or molecular gas (eg. Cowie 1980; Balbus and Cowie 1985). We here present a phenomenological model for GMC, whereby the rate of their formation, and CO emission, depends on the rate at which a parcel of gas encounters a spiral perturbation, and on the square of the HI density. We are most interested in understanding the *radial profiles* of CO in disk galaxies – why they are so different from the atomic gas profiles, but similar to the blue light. In this respect it is only important that the progenitors of GMC have the same radial profile as the HI, as may be the case for the analogs of the small high latitude CO clouds found by Blitz, Magnani and Mundy (1984). Thus

$$CO(r) \propto n_{HI}^2(r)(\Omega(r) - \Omega_P)m$$

where Ω is the local angular frequency, Ω_P and m being the pattern speed and number of arms in the spiral pattern. For situations where no underlying density wave occurs but the arms are due to a simple shear instability and swing amplifier, we set $\Omega_P = 0$, since then $\Omega(r)$ mimics the Oort constant of differential rotation, which controls the instability (Toomre 1981). A dependence on the rate of encounters of spiral arms was also postulated by Shu *et al.* (1972) in their modelling of the SFR in density wave theory, and by Güsten and Metzger (1982) for massive stars in the spiral arms of our Galaxy. The dependence on the square of the HI density assumes that two-body processes such as binary cloud-cloud collisions dominate. We are also equating a rate with a luminosity and hence mass.

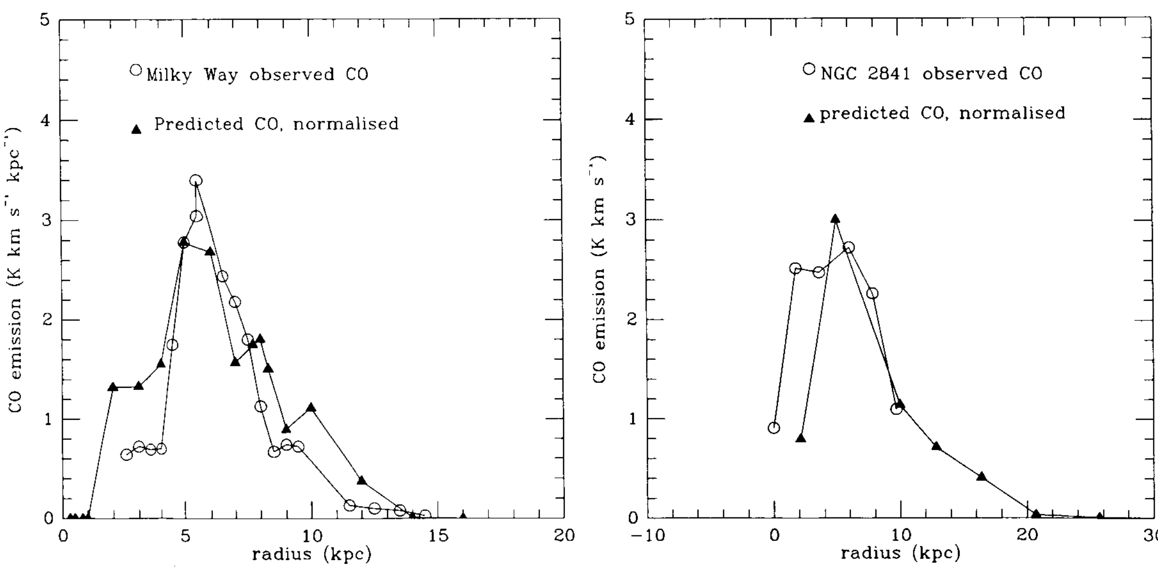

Figure 1. Predicted CO emission (filled triangles), arbitrarily normalised, compared to the observations (open circles) for the Milky Way (Sanders, Solomon and Scoville 1984) and NGC 2841 (Young and Scoville 1982).

We have made predictions for of order ten galaxies with the necessary observations, obtaining encouraging results. Interesting features are that galaxies which are believed to have a density wave are best fit by corotation in the outer regions, as predicted by theory (Shu *et al.* 1972) and have a significantly poorer fit if we set $\Omega_P = 0$, while the galaxies with more filamentary arms (eg NGC 2841) are well fit by the theory for arbitrary values of the

pattern speed, as may be expected. Results for the Milky Way and NGC 2841 are shown in Figure 1. We obtain equally good agreement with the CO observations for galaxies with a CO 'ring' and those with monotonic CO. The radial fall-off of the CO emission to large radii while the HI remains flat reflects the near exponential behavior of $\Omega(r) - \Omega_P$, which in turn reflects the profile of the stellar disk since disk galaxies are essentially self-gravitating within a few scale-lengths. Thus fitting an exponential to the CO results in a scale-length close to that of the stars, or equivalently, the blue light.

3. CHEMICAL EVOLUTION IN A BIMODAL MODEL.

Any reasonable model for the time dependence of the gas mass, together with the regulation equation above, yields a massive SFR that decreases sharply with time. This contrasts strongly with the derived constant Solar Neighborhood low mass SFR (Twarog 1980) – hence the star formation process is bimodal in time as well as space (cf Larson 1986). Matteucci and Greggio (1986) showed that a constant SFR for stars of all masses would overproduce oxygen and other elements due to massive stars. The effect of the new $^{12}C(\alpha,\gamma)^{16}O$ reaction rate on the chemical yields of massive stars was investigated subsequently (Matteucci 1986) and silicon and iron are still overproduced. A decreasing massive SFR appears to offer a solution.

We have investigated the chemical evolution in a particular parameterisation, where the two modes are taken to be 1). 'low mass' mode : Miller-Scalo IMF, all masses, constant SFR $A_1 M_\odot Gyr^{-1}$ and 2) 'massive' mode : only stars above M_{L2}, SFR $A_2 e^{-t/\tau_2} M_\odot Gyr^{-1}$. The lower mass cutoff of the 'massive' mode is made as low as possible, to avoid introducing a time dependence into isotopic ratios which would arise were the nucleosynthetic properties of the two modes different and which is not observed. The models are required to fit the Solar Neighborhood age-metallicity relationship for low mass F stars and also to reproduce the present day gas content and total disk surface density, 70 $M_\odot pc^{-2}$ (any dark matter being stellar remnants). A gas consumption time of at least several Gyr is also required. These quantities are shown in Figure 2 for a model we deem satisfactory.

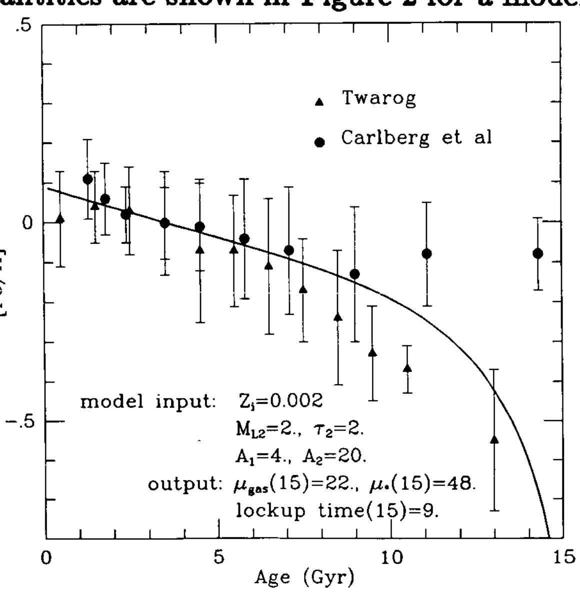

Figure 2. The predicted age metallicity relation for long-lived F stars in the Solar Neighborhood (solid line), for a model for the thin disk with initial metallicity a tenth solar, consistent with the spheroid model in Figure 3(b), and with low mass mode SFR 4 $M_\odot Gyr^{-1}$, high mass mode, with lower mass of 2 $M_\odot$, normalisation 20 $M_\odot Gyr^{-1}$ and e-folding time of 2 Gyr. The observational data of Twarog (1980) and Carlberg *et al.* (1985) are also shown. The model and observations are in good agreement, and the model output values, at 15Gyr, for the gas and stellar surface density μ $M_\odot pc^{-2}$ and the gas lockup (consumption) time are entirely satisfactory, although the gas content is somewhat high.

We have also compared model predictions with the cumulative metallicity distributions of thin disk stars and extreme spheroid stars, allowing for ejecta from the spheroid (leaving at a rate λ times the star formation rate) to pre-enrich the thin disk material (see Figure 3). There is a narrow range of parameter values which provides a good fit to *all* these observational constraints.

We are currently working on fully self consistent models, using the equations above for the time and radial dependences of the massive SFRs. Extension of the model to different environments such as IRAS galaxies is underway to help understand the starburst phenomenon.

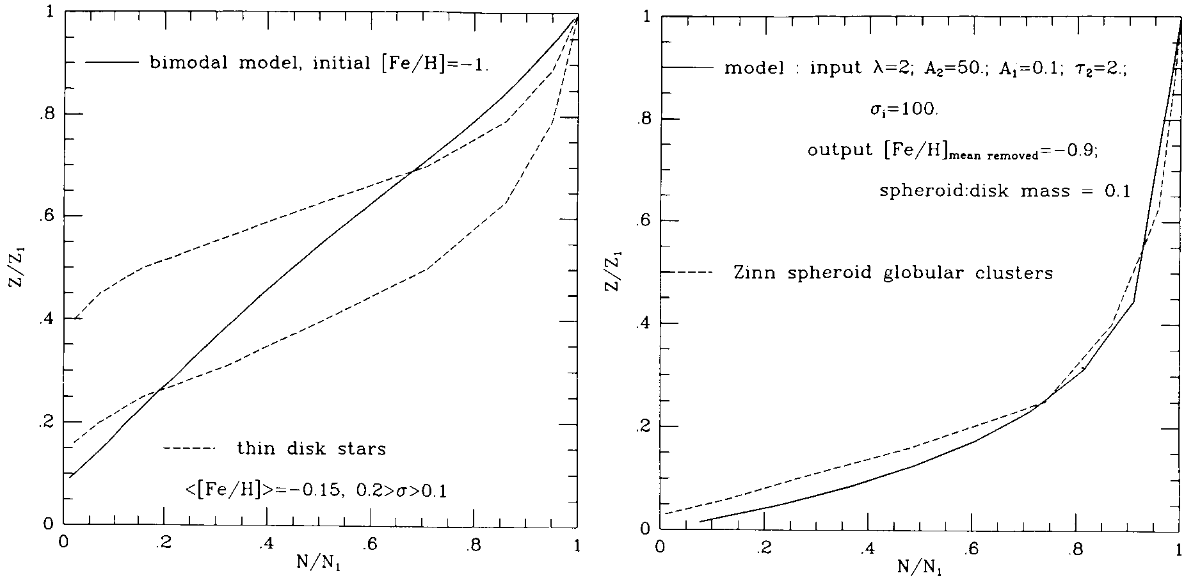

Figure 3 (a). Cumulative metallicity distribution for the low mass stars of our favored model (solid line) compared to estimates of the true distribution, which are $\pm 2\sigma$ truncated gaussians, of mean -0.15 dex (dashed lines delimiting range of dispersion $0.1 < \sigma < 0.2$ dex).

(b). Cumulative metallicity distribution for spheroid stars. The model (solid line) has star formation parameters as indicated, with outflow at twice the total SFR, and a total initial surface density (σ_i) of $100 M_\odot pc^{-2}$. The observations are the metal poor spheroid globular clusters (Zinn 1985). The model predicts reasonable values for the initial enrichment of the thin disk and for the spheroid to thin disk mass ratio.

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